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# **Stratified Coastal Trapped Waves and Mean Flows**

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## **LONG-TERM GOALS**

Our long term goals are to identify the roles that rectified subinertial waves and mesoscale motions play in the mean-flow transport of fluid properties in the coastal ocean and to apply these ideas to cross-margin transport of physical, chemical, and biological properties. In addition, we are interested in the interaction and relative effect of wave-driven transport versus frictionally driven boundary layer transport.

## **OBJECTIVES**

Coastal waves and wave-generated mean flows are studied in a stratified, rotating model ocean. Waves trapped to the coast are generated by time-dependent flow over a sloping and irregular bottom. We study flow resulting from oscillatory flow over a sloping bottom, both with and without stratification, and with and without additional topographic features. Short-term goals of this study include quantifying the vertical structure of the along-slope mean flow driven by non-linear interactions of the coastal trapped wave and asymmetries in Ekman bottom boundary layer development. The effects of stratification on the cross-slope overturning circulation will be examined to evaluate the strength of wave-driven mean flow verses frictionally driven flow.

## **APPROACH**

The approach for this research was to use laboratory experiments and two types of numerical models. The laboratory experiments are fully non-linear by their very nature, while the numerical models provide a useful venue for studying specific processes and offer much better diagnostics.

In the lab experiments, a bowl-shaped tank with radial ridges provides the coastal slope and cross-slope topography to generate wave motions. The entire apparatus rotates and flow over the topography is achieved with a slight spin-up or -down of the rotation rate. The water in the bowl is stratified with salt to give a vertical density gradient. Waves are generated by the topography and trapped to the coast by the planetary rotation. The fluid motions are observed by tracking the paths of neutrally-buoyant particles at multiple vertical levels. The initial and evolving stratification is measured with a micro-CTD probe.

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Two numerical models are used. One is the coastally trapped wave model developed by Ken Brink and Dave Chapman at WHOI for the study of the linear response, and a fully non-linear isopycnal numerical model is being used to directly simulate the laboratory experiment with laboratory geometry and parameters.

The approach that we will take here is to build do a series of laboratory experiments each with additional physical complications. In the laboratory experiments, we will do experiments both with a bowl-shaped tank, and with a bowl shaped tanked with four radial ridges to generate wave-driven motions and study the rectified motion resulting from oscillating the rotation rate of the tank and the interaction of friction, wave-drag, and stratification. Numerical experiments will be done in parallel to simulate the stratified problem to be able to diagnose the causes of any rectified circulation observed.

In addition to the isopycnal numerical model that is used to simulate the laboratory experiment, work is completed on a semi-analytical study of wave-mean flow interactions of topographic Rossby waves that are the quasi-geostrophic equivalent of coastally trapped waves. Work is nearly complete testing a new formulation of the overturning circulation in a stratified fluid where topographic slope is large, such as on the continental slope. This analysis of possible mean-flow formulations may help in better parameterizing ocean the effects of eddies in large-scale general circulation models when the influence of topography cannot be ignored.

## **WORK COMPLETED**

1. The numerical model has been configured for the laboratory experimental configuration (Qualitative comparisons to the laboratory experiments have been done. Analysis of the numerical experiments is currently being completed by an undergraduate funded by a University of Washington Mary Gates Research Fellowship. He will continue to work with us until he graduates in June.
2. Weakly non-linear analysis in a quasi-geostrophic setting has been completed and a paper has been submitted. It is currently under revision.
3. A new formulation for the residual circulation ( the cross-slope circulation of mass in the quasi-linear problem of wave-mean flow interaction) has been developed has been applied to output from the Brink and Chapman model.
4. With the loss of Dr. Daniel Ohlsen to the project in 1998, we moved the laboratory experiments to the University of Washington, and we recruited Dr. Boris Boubnov, visiting from Moscow University to complete the laboratory experiments. In the space of two months, Dr. Boubnov performed over 130 experiments. With various visualization techniques, we have shown two distinct flow regimes, depending on whether the flow is homogeneous or stratified. Parallel numerical experiments were done and diagnostics were done on the model. Unfortunately, Dr. Boubnov passed away in the summer of 1999, so that the completion of the paper describing the laboratory work has been delayed. With Dr. Rhines and help from the undergraduate as described above, we expect that a paper will be completed this spring.

## IMPACTS/APPLICATIONS

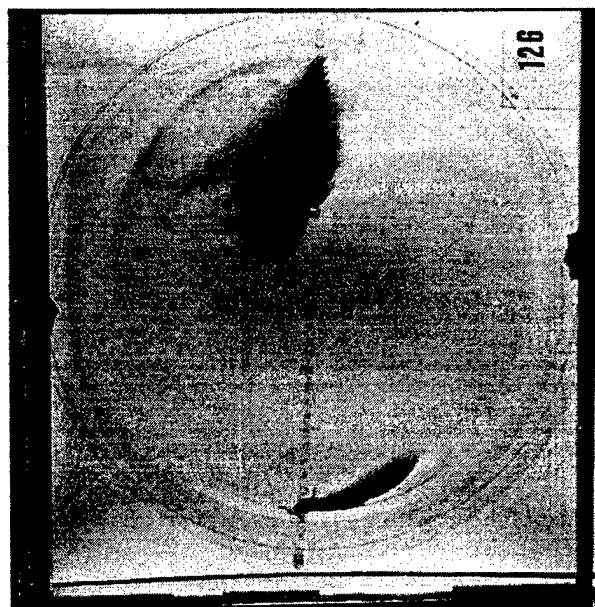
The implications of this work is that mean flow and mass flux associated with wave-driven and boundary layer driven processes are comparable. In fact, neither can be ignored using the laboratory scaling. While the consideration of transport processes associated with boundary layer flow is commonly considered in coastal oceanography modeling, wave-driven processes should also be considered.

## RESULTS

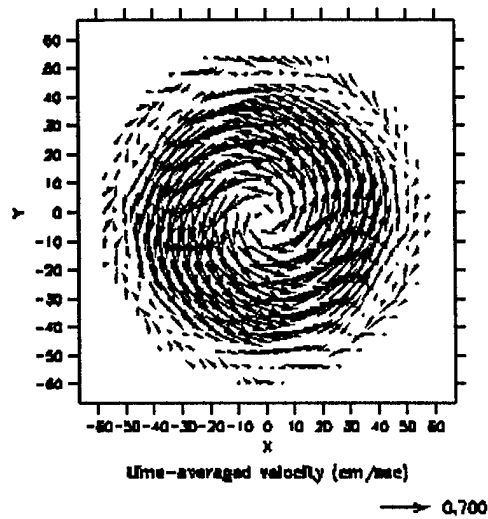
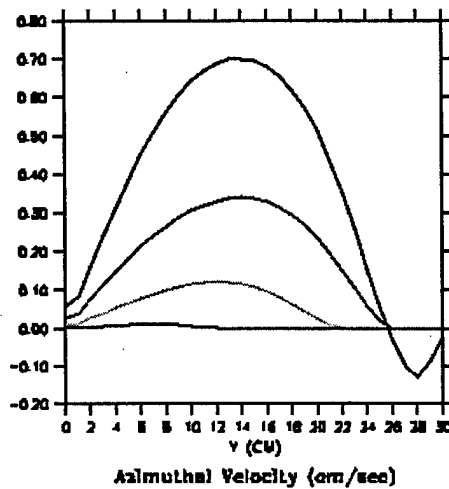
We find that the qualitative evolution of the mean flow (average azimuthal velocity) is independent of the form of the frictional parameterization, but the time-scale over which the azimuthal velocity slows does depend strongly on friction, although the structure does not (Figure 2). This suggests that wave-mean flow interaction for coastally trapped waves is relatively independent of the frictional parameterization in its structure, although the magnitude of the effects on the mean-flow do depend on friction.

Results from the laboratory experiments shows that in homogeneous fluid, in the absence of topographic ridges, there is net mean flow in the cyclonic direction, in the direction that Kelvin waves and coastal trapped waves travel (Figure 1). A similar flow can be seen in the numerical experiments (Figure 2). In contrast, when the fluid is stratified and there are no ridges, the flow is anticyclonic. This results from fundamental differences with the boundary layer structure when the flow is stratified and there is a sloping bottom. Using the ideas of MacCready and Rhines (1991) a simple analytical solution was derived and it was shown that for laboratory scaling, the resulting mean flow would be on the order of the oscillatory flow. The laboratory parameters allow a scale separation between the spin down time for cyclonic flow and anticyclonic flow. However, when ridges are included in either the homogeneous or stratified experiments, the resulting flow is for the most part cyclonic. There is a small band of anticyclonic flow at the outer rim of the bowl in the stratified experiments. Numerical experiments using laboratory scaling show similar results both in the stratified and unstratified cases. The resulting azimuthal and temporal mean flow shows that the flow is largest near the surface and is maximum about half way into the tank. In the numerical model, the mass-flux can be calculated. The resulting mass flux is consistent with mean flow generation and the resulting modification of the density field and thermal wind. There is a flux of mass towards the center of the bowl near the bottom, with a more diffuse return flow throughout the rest of the fluid (Figure 3).

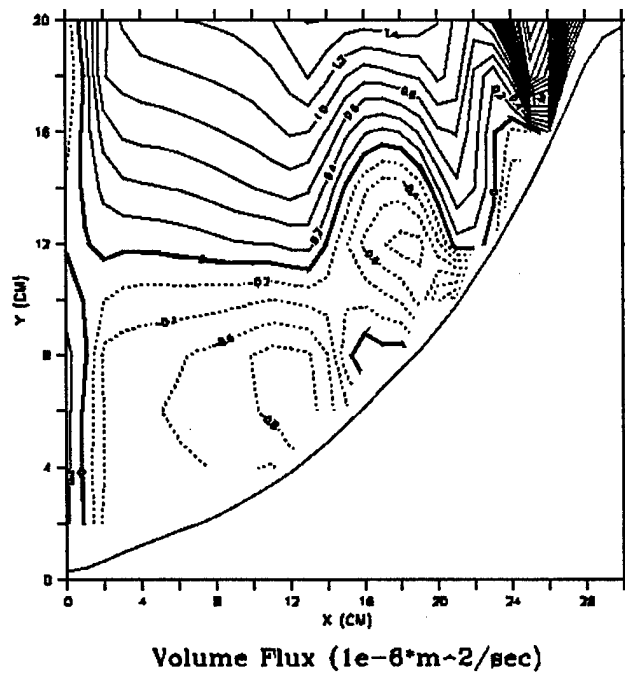
The new formulation for the residual circulation ( the cross-slope circulation of mass in the quasi-linear problem of wave-mean flow interaction) shows that there are significant differences between a formulation that does not allow transport into the bottom, and the more traditional formulation that does not allow transport through the surface. A paper is in preparation on this work.



**1. Tracer distributions from the laboratory experiment. Upper right hand corner shows the initial release point of the tracers for the homogeneous experiments in a smooth bowl. Below that show the tracers some time later. The tracers are advected cyclonically throughout the fluid. The upper left hand corner shows the release points of the tracers for the stratified experiment with ridges on the bowl. Below that shows that the tracers are advected anticyclonically near the rim, and cyclonically in the interior.**



2. Left panel shows mean flow that is generated in the numerical model with stratification and ridges as a function of radial distance for each of 4 layers. Note the predominantly cyclonic flow, and the reversed flow near the rim. Right panel shows a plan view of the upper layer flow.



3. Mass flux calculated in the numerical model. Note the mass flux towards the center of the bowl near the bottom, and the more diffuse return flow near the surface. Note also the strong positive mass flux near the rim, associated with the flow reversal.

## PUBLICATIONS

Papers that we have been submitted or will be submitted shortly on this work

1. Thompson, L. and F. Evans, Topographic Rossby-wave mean flow interaction submitted to *Journal of Marine Research*.
2. Thompson, L. Coastal trapped wave-mean flow interaction. In preparation for *Journal of Physical Oceanography*.
3. Thompson, L. and P.B. Rhines: Laboratory study of stratified coastal waves and mean flow, to be submitted to the *Journal of Fluid Mechanics*.